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Heavy Particle Identification with a T. O. F. Method in Nuclear Reactions

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Particle identification system with a T. O. F. method is developed to accomodate the high repetition rate of the cyclotron beam of 13 MHz. Starting signals of the T. O. F. system are obtained from a tantalum plate in the course of a bunched beam from the Kyoto University cyclotron. Stop and energy signals are obtained from a solid state detector. An experiment on the p-d scattering at $E_p = 7.3$ MeV shows that protons and deuterons are identified clearly with each other. The time resolution was estimated to be of 2.6 ns but finally was improved to be of 1.5 ns by adding a diode limiter circuit to the T. O. F. system.

I. INTRODUCTION

It has been proposed by many authers[1] that a ^{6}Li and a ^{7}Li nuclei have α+d and α+t structures respectively. If so, the ^{6}Li and the ^{7}Li neuclei are thought to be a kind of cluster carriers such as d, t, and α. Moreover, if one assumes the cluster pick-up reaction mechanism, the heavy particle producing reactions such as (d, ^{6}Li), (α, ^{7}Li) and so on are useful tools to investigate the cluster structure of the target nuclei.

In our laboratory, alpha cluster structure of light nuclei has been investigated by using (α, 2α) and (p, pα) reactions.[2] As a natural development of research, we are interested in the heavy particle production reactions.

In earlier experiments, protons, deuterons and alpha particles were the main objects of our detection system, and a ΔE-E counter telescope system worked well to identify these particles. However, if heavy particles should be detected, this system is no longer useful. The reasons are as follows.

1) Because the charge states of heavy particle have freedom of wide range, the pulses from the ΔE counter is multi-valued even if the energy is fixed. Then one could not identify easily the heavy particle.

2) Because the energy loss of a heavy particle is very large, a ΔE counter stops completely the heavy particles produced in the low energy reaction such as studied in our laboratory. Then we can not afford a relevant ΔE-E telescope system.

These difficulties could be removed if one measures directly the velocity and energy of the particle. A T. O. F. method coupled with a total energy detection system, not a ΔE-E telescope system, is therefore suitable for the heavy particle identification.

At present, the Kyoto University Cyclotron produces a bunched beam of 13 MHz

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repetition, then one should modify the T. O. F. method to accomodate such high repetition.

Heavy particle identification system with the T. O. F. method in conjunction with a total energy detection, has been proposed by several authers[3] and successfully used in the pulsed beam experiments,[4] but there are few studies to use this system in the ordinary cyclotron experiments. In this report, a heavy particle identification system suitable for the high repetition cyclotron experiments is described.

II. PRINCIPLE OF IDENTIFICATION OF HEAVY PARTICLES

Flight time t of a particle of energy E over a distance d is given by the next formula in the non-relativistie limit.

$$t = 0.723\,d(m/E)^{1/2}\,, \tag{1}$$

where t, d and E are in units of nsec, cm, and MeV respectively and m is the mass number of the particle. The product Et^2, for a given d, depends on mass of the product particle only and therefore simultaneous measurement of E and t identifies the mass of the particle. If various reaction products of the same mass are produced, for instance ^{6}He, ^{6}Li *etc.*, Q values are in most cases different and the kinematic condition can usually determine the particle; the pulses of particles can be selected when a two dimensional representation is made between E and t or E versus Et^2 with the aid of a multiplying circuit.

From eq. (1)

$$\Delta m/m = \Delta E/E + 2\,\Delta t/t\,. \tag{2}$$

$\Delta E/E$ is negligible for semiconductor detector, so that substituting t by Eq. (1), Eq. (2) gives,

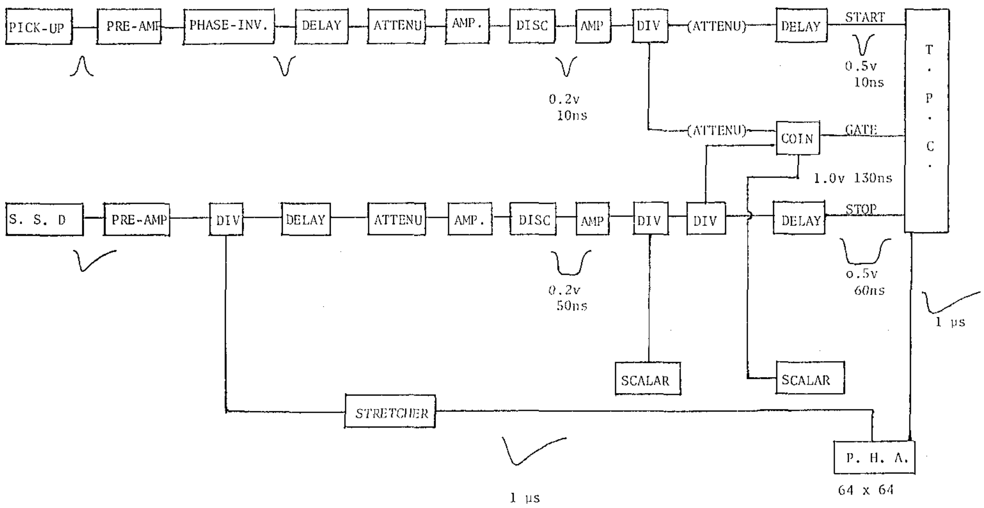


Fig. 1. Block diagram of the circuit system

$$\Delta m/m = 2\cdot(\Delta t/0.723\,d)\,(E/m)^{1/2}\,. \tag{3}$$

Eq. (3) indicates that the resolution $\Delta m/m$ becomes better with the lower energy and heavier particles. Therefore T. O. F. method is suitable to identify the heavy particle of low energy.

III. ELECTRONIC CIRCUITS

The block diagram of electronic system is shown in Fig. 1. The circuit parameters were adjusted to accomodate the RF frequency of 13 MHz. The time walk at the

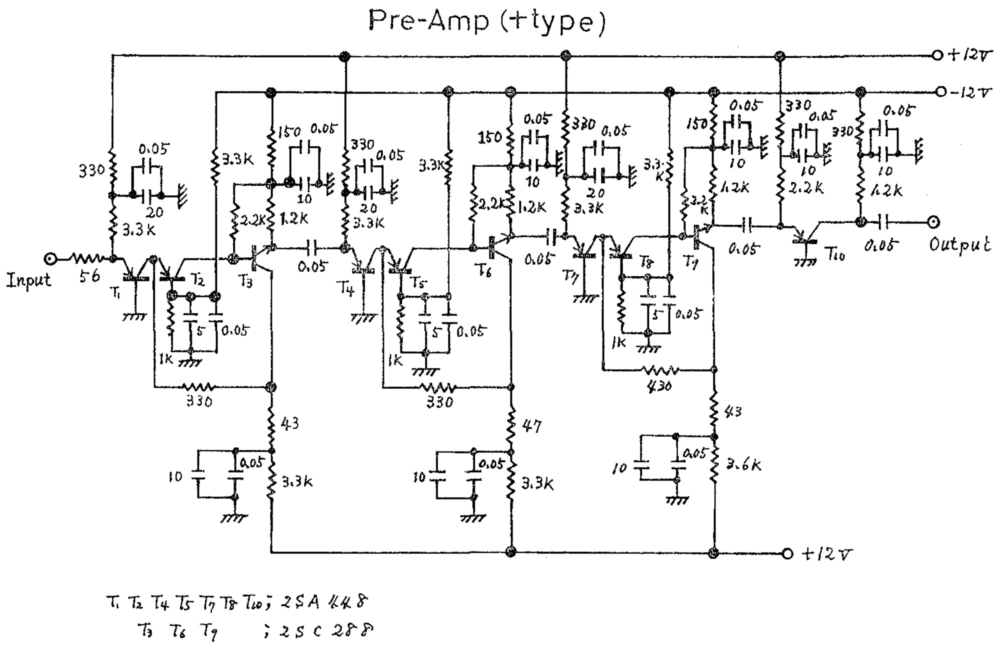


Fig. 2. Circuit diagram of the pre-amplifier

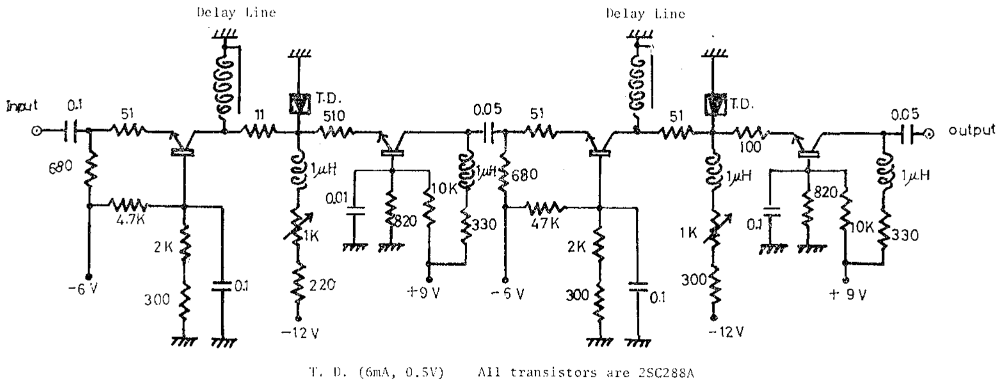


Fig. 3. Circuit diagram of the discriminator

discriminator due to the input pulse height variation was lessened by using fast rise time pre-amplifier.

The pre-amplifier was built after the design of Papadoplos,[5] of which the circuitry is shown in Fig. 2. It has the gain of 200 and the rise-fall time of 3 ns and was connected to the positive pulses from a pick up probe.

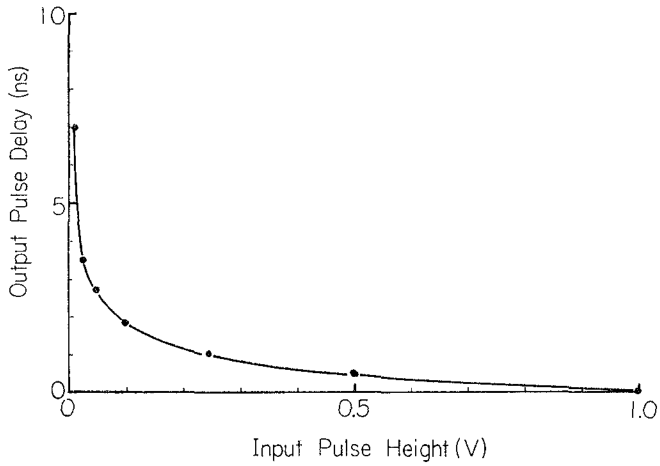


Fig. 4. Time delay of output pulse of the discriminator as a function of the input pulse height.

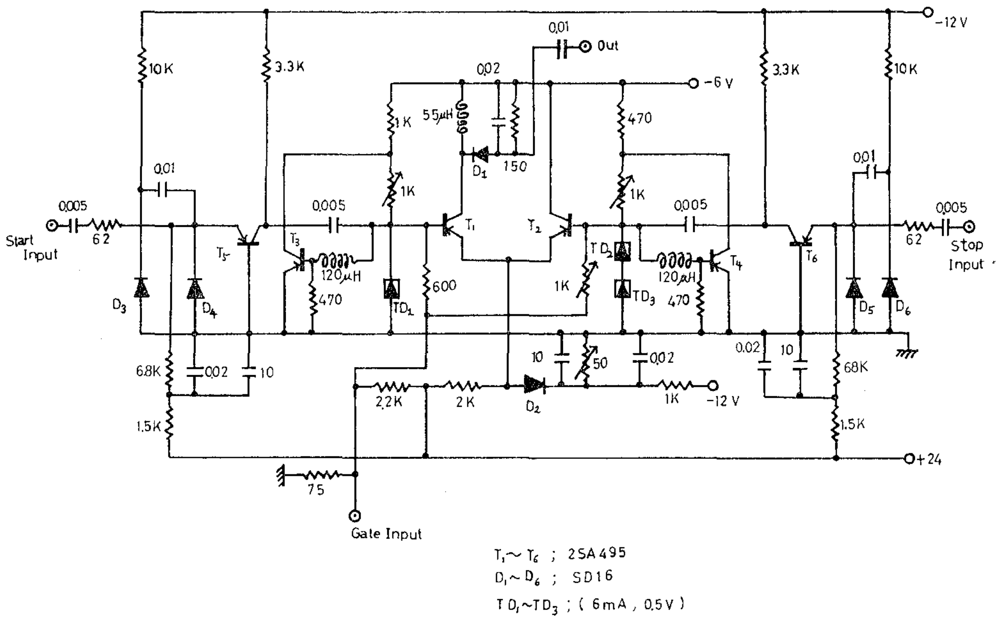
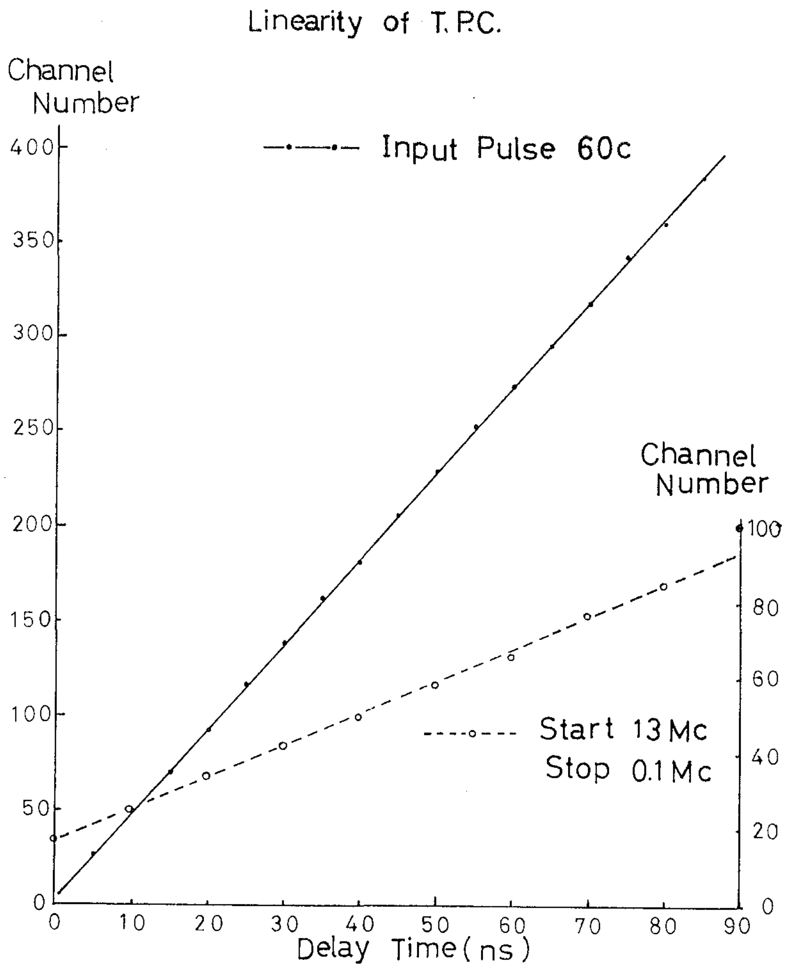


Fig. 5. Circuit diagram of the time to pulse height converter (T. P. C.)

The pre-amplifier of the negative pulses from the solid state detector has the gain of 100 and of 2 ns rise time, and the circuitry is shown in Fig. 3 of ref. (7).

The circuit diagram of a discriminator is shown in Fig. 3, where two sets of discriminators are connected in series in order to prevent the high input pulses to go through. The output pulse width is determined by the length of the delay line. The dead time is of 50 ns duration and less than the start pulse period of 77 ns. The characteristics of the discriminator is shown in Fig. 4.

The time to pulse height converter shown in Fig. 5 is the same type as that was designed by Ophir.[6] The time constant of LC circuit determines the linear range of T. P. C.. The period of the start pulse is of 77 ns. Therefore the values of L and C are set so that the linear range is of 80 ns. Pulse heights and widths of the start, stop and gate pulses are, 0.5 volt and 10 ns, 0.5 volut and 50 ns and 1.0 volt and



—·—·—; measured with 60 Hz pulses
--o--o--; measured with 13 MHz start and 0.1 MHz stop pulses

Fig. 6. Linearity of the T. P. C.

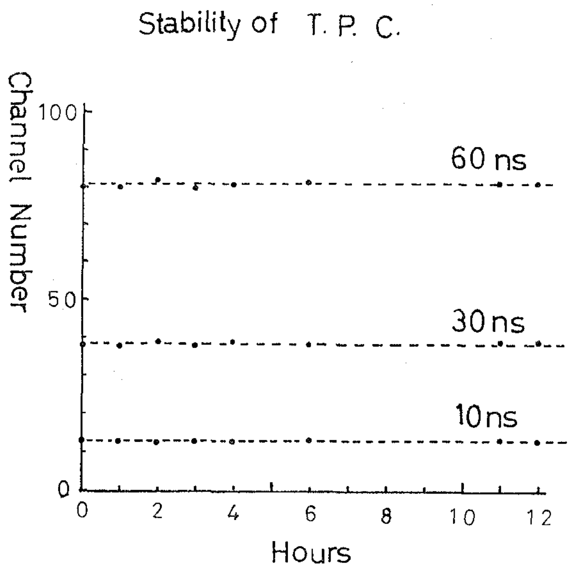


Fig. 7. Stability of the T. P. C.. The figures 10 ns, 30 ns and 60 ns denote the delay time of the stop pulse to the start pulse. The time scale is 0.9 ns/ch.

100 ns respectively. The linearity of T. P. C. is shown in Fig. 6. Analyzing the output pulses from T. P. C. by a 1000 channel P. H. A., the resolution was estimated to be of 0.2 ns. The stability is shown in Fig. 7 and it is estimated to be 1%.

By varying the pulse heights fed to the discriminator from 0.1 volt to 1.0 volt and observing the shift of the pulse heights from the T. P. C., the time walk is estimated to be of 1.8 ns.

The coincidence circuit system was tested to have a coincidence efficiency of 100% in the case of 13 MHz start and 0.1 MHz stop pulses.

Circuit diagrams of linear amplifier, coincidence and stretcher are shown in Figs. 5, 18, and 23 of ref. 7 respectively.

IV. EXPERIMENTAL RESULTS

7.3 MeV proton beam from the 105 cm ordinary cyclotron of Kyoto University bombarded a self supporting foil of deuterated polyethylene (CD_2) film of about 1 mg/cm^2 thickness, which was set at the center of 45 cm diameter scattering chamber. ORTEC 500μ-thick surface barrier SSD was placed at a distance 56 cm apart from the target and at the angle of 27.5° with respect to the beam axis. A slit of 5 mm diameter was set in front of the detector and the solid angle subtended by the detector was 2.6×10^{-4} sr. A beam pick-up probe shown in Fig. 8 was set in the beam course at a distance of 15 cm behind the target.

Output signals from the pre-amplifier of the beam pick-up probe is shown in

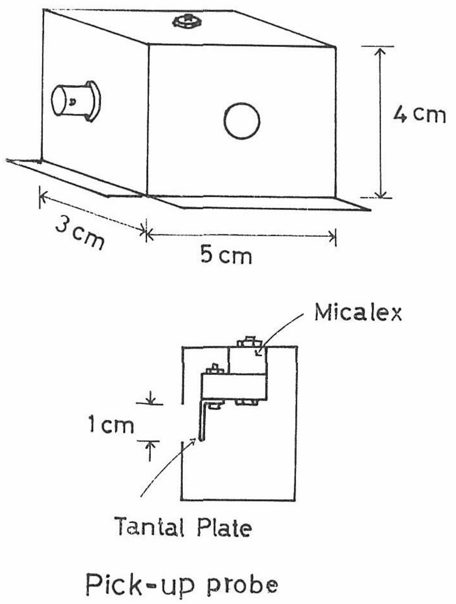


Fig. 8. Schematic drawing of the beam pick-up probe. The beam is collected by a tantalum plate of 1 mm thick. The area of the plate is 1 cm × 1 cm. The current signal is transmitted to the BNC connector through the copper wire. Copper box with a 1 cm diameter hole shields the R. F. signals from the oscillator. The micalex insulates the probe from the grounded box.

Photos 1 and 2. The intensity of H_2^+ ion beam is about 50 nA. The pulse height is of 150 mV and the width at half maximum is less than 10 ns (about 6 ns). High Energy group of Kyoto University[8] showed in their T. O. F. experiment using the Kyoto University Cyclotron that the one bunch width of H_2^+ ion beam is of about 1 ns, therefore, the width of the one bunch beam could be less than the value obtained in this experiment. The height of RF signal is 20 mV and the S/N ratio (the ratio of beam signal to the RF signal) is found to be 7. Photo 2 shows beam modulations. Photo 3 indicates the proper operation of the discriminator. From the cable curve (Fig. 9) the coincidence width is estimated to be of 65 ns (equals to the sum of the width

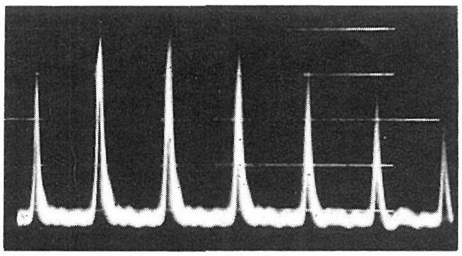


Photo. 1. H_2^+ ion beam signal at the output of the pre-amplifier. Maximum height is 160 mV and the repetition period is 77 ns.

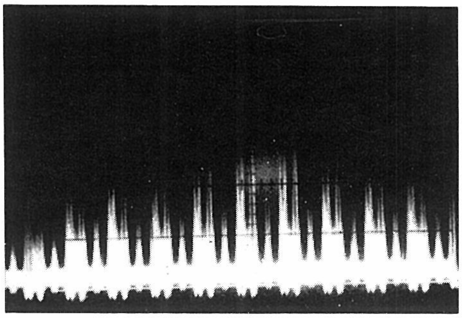


Photo. 2. Modulation of H_2^+ ion beam intensity. 120 c/sec modulation is due to the ripple of arc voltage of the ion source and the 360 c/sec modulation is due to the ripple of dc power supply of RF accelerating voltage.

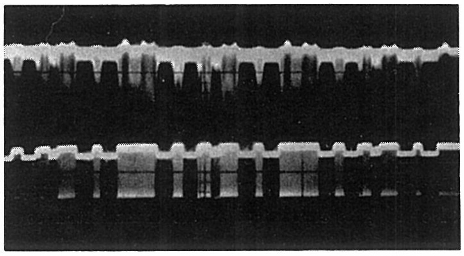


Photo. 3. Wave form of the start pulse at the input (upper side) and the output (lower side) of the discriminator.

of start and stop pulses, 10 ns and 50 ns respectively). The beam pick up efficiency, defined by the ratio of coincident counts to stop signal counts, is estimated to be 95%. As the experiment was carried out at a fixed angle, energy and time scales were obtained in terms of a variable attenuator and a variable delay line. These were 105 KeV/ch. and 1.3 ns/ch. respectively.

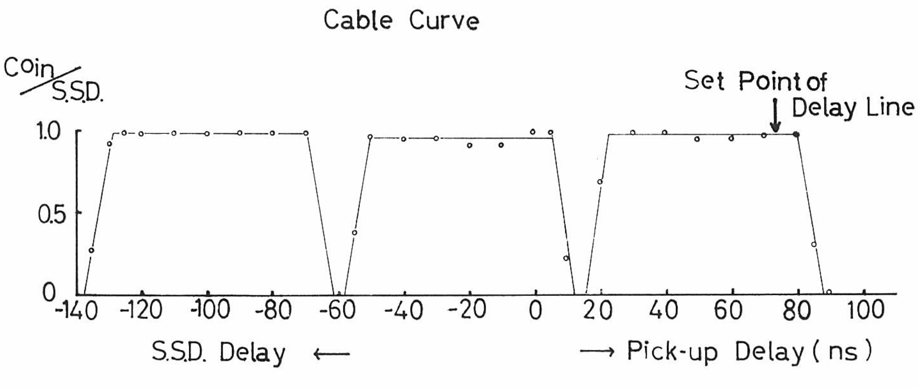


Fig. 9. The ratio of the coincidence counts to the stop pulse counts as a function of the relative delay time of the start and stop pulses.

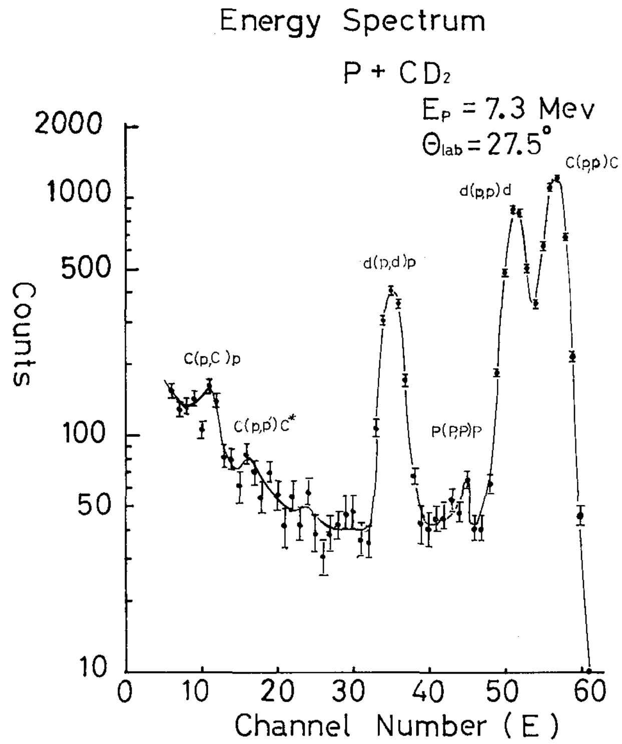


Fig. 10. Energy spectrum of products from the reaction $p+CD_2$ $E_p=7.3$ MeV, $\theta_{lab}=27.5°$.

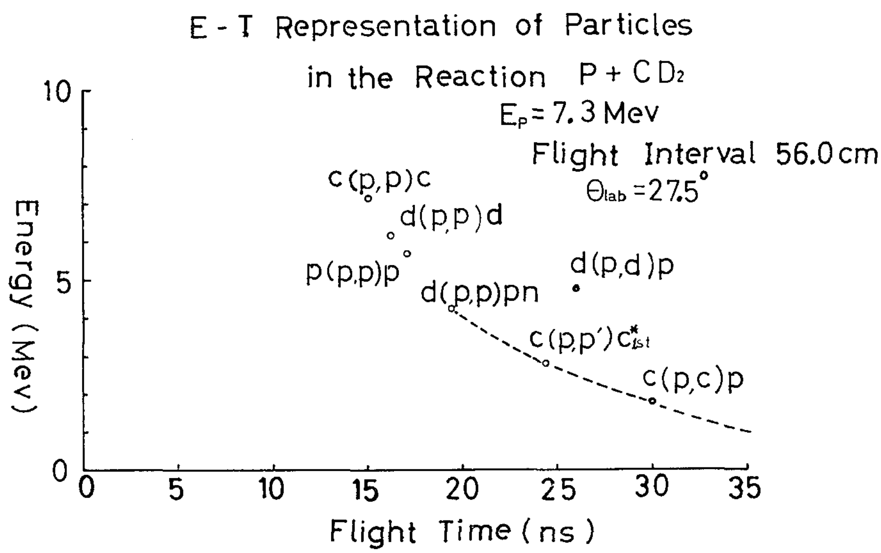


Fig. 11. Calculated values of energy and flight time for the reaction of $p+CD_2$.

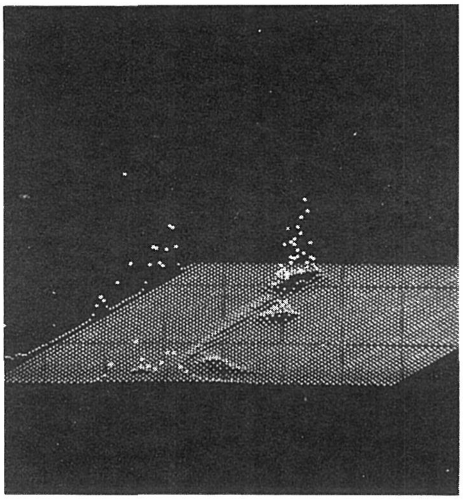


Photo. 4. Isometric view of the spectrum obtained using the reaction $p+CD_2$. X-axis shows the flight time and the Y-axis shows the energy of product particles.

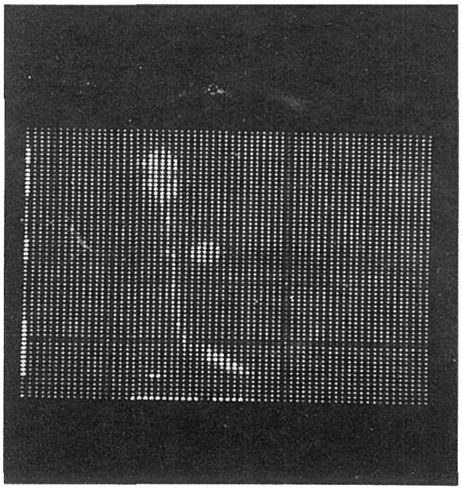


Photo. 5. Display of Photo. 4 in the 64×64 channel mode. Each peak corresponds to the figure in Fig. 11.

The energy spectrum is plotted in a logarithmic scale in Fig. 10. Photo 4 shows the isometric representation of coincidences between energy and flight time pulses and Photo 5 is its two dimensional spectrum in 64×64 channel mode.

Each peak in Photo 5 can be identified by the kinematics shown in Fig. 11. The peak of recoiled carbon is late by one period *i.e.* 77 ns..

In order to estimate the time resolution, time spectra are plotted in Fig. 12, representing the velocity distribution of respective energy particles. The full width at half maximum of each peak is 2 channels or 2.6 ns. In the case of carbon detection,

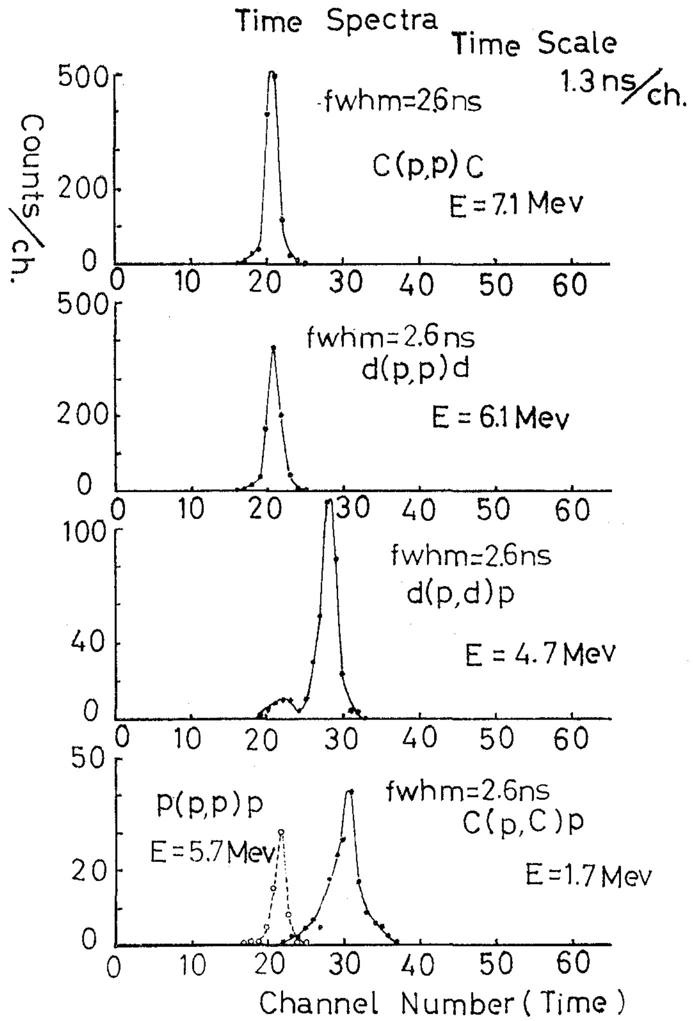


Fig. 12. Time spectra at the peaks in the energy spectrum of Fig. 10.

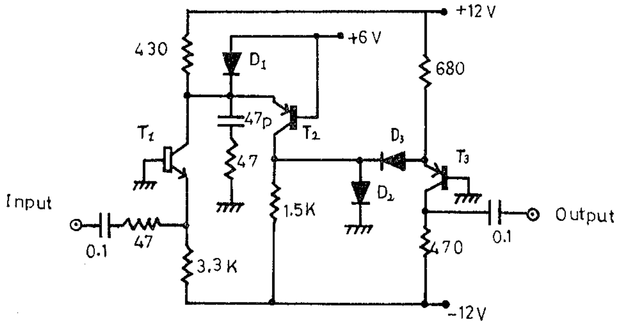
the width is 3.9 ns due to the overlap of the proton background and the carbon peak. Hence the time resolution is estimated to be 2.6 ns.

V. DISCUSSIONS

Following factors can be the cause of errors in the time resolution.

1. One bunch width of pulsed beam; $\Delta t_1 \leqq 1$ ns
2. Time resolution of TPC; $\Delta t_2 \simeq 0.2$ ns
3. Timing fluctuation of output pulses from the surface barrier S. S. D.; $\Delta t_3 \leqq 1$ ns
4. Time walk in the discriminator due to the pulse height variation of the start signal; Δt_4

(It is reported that the surface barrier detectors have 1 ns or better timing resolution inherently[9]).



D1 ∿ D3; SD16
T1 ; 2SC288A
T2, T3; 2SA488A

Fig. 13. Circuit diagram of the limiter.

The experimental time resolution is 2.6 ns and then

$$(\Delta t_1^2 + \Delta_2^2 + \Delta t_3^2 + \Delta t_4^2)^{1/2} \simeq 2.6 \text{ ns} .$$

From this relation, the time walk due to the pulse height variation of the start signal is estimated to be 2.0 ns.

In order to improve the time resolution, time walks should be lessened in the first place to the value of about 1 ns. Next two methods were carried out and proved to be useful. First, the use of a limiter which delays the high input pulses by the effect of saturation. By inserting the diode type limiter circuit, shown in Fig. 13, in front of the start timing discriminator, time walk was reduced to 1 ns for the input pulse ranging from 0.1 to 0.5 volt. Second, the S/N ratio of the beam signal to the background should be improved. S/N ratio was improved to the value of 10 by replacing the beam pick up probe with a slit type one and setting it at the objective of the beam analyzing magnet. The beam intensity at that point is about ten times stronger than at the former point. In conclusion, the time resolution was improved to 1.5 ns which was ascertained with an experiment on p-d scattering.

From the Eq. 3, lower than 20 MeV Li ions can be distinguished from alpha particles, deuterons and protons with the E-T two dimensional analysis if the flight path is of 20 cm length and if the time resolution is equal to or less than 1.5 ns. To shorten the flight path to the length of 20 cm, has the following two merits.

1) The angular distribution spectrum can be easily obtained with a detector set within the 45 cm diameter scattering chamber.

2) The short path length gives a larger solid angle. This large solid angle enables the study of the rare event reactions such as (α, ^{6}Li) reactions.

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